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Mean strain effects on the strain life fatigue curve

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MEAN STRAIN EFFECTS
ON THE
STRAIN LIFE FATIGUE CURVE

by

Byron L. Smith
Lieutenant, United States Navy
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ABSTRACT

Aluminum 7075-T6 was tested using a Fatigue Material Test System. After creating the monotonic and cyclic stress-strain curves to verify material properties, strain life test data were replicated twenty times each to obtain the statistical description of a standard strain life curve for zero mean strain. The mean strain was then varied to create a total of four statistically described curves. Accounting for the statistical distribution, various characteristics were plotted in order to better understand the effects of mean strain. For example, strain range was plotted against the mean strain for given lives and results were compared to equations in use today that account for mean stress.

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ACKNOWLEDGMENT

I would like to express my appreciation to the professionals affiliated with the Naval Postgraduate School. Their assistance given me was vital to the completion of this study. I would like to thank Mr. John Moulton for his time and effort spent on making over 400 test specimens at the school's facility, thereby saving time, and more importantly, the Navy's money. Further thanks are due to the Mechanical Engineering Department and Mr. Jim Scholfield for the use of the department's MTS machine and Mr. Scholfields' knowledge and assistance. Without the help of the above mentioned, this testing would not have been possible.

I. INTRODUCTION

Cyclic fatigue properties of a material are obtained from completely reversed, constant amplitude strain-controlled tests. Components seldom experience this type of loading, as some mean stress or mean strain is usually present. An aircraft load history is a perfect example. The majority of time, during a typical mission profile, the aircraft experiences 1 g loads with excursions above and below.

The Strain life approach is the method employed by the Navy to predict fatigue life. Current practice is to only address the mean stress effects on the strain life curve. Considering that some current aircraft, and all newer ones, will most likely utilize strain gage data to determine aircraft life, it is important to understand the statistics of the strain life approach, the effects of mean stress and strain and varying load history effects. Recent studies at the Naval Postgraduate School have researched aircraft load histories and how best to model them. Further strain life analysis is necessary to assist in this endeavor.

Crack growth is not explicitly accounted for in the strain life method. Because of this, strain life methods are often considered "crack initiation" life estimates. Initiation of a crack in an aircraft is considered very critical by the Navy and constitutes the end of life for that component. It is believed that the results of this thesis provide a better understanding of mean strain influences on fatigue life crack initiation.

II. TEST FACILITY

The Mechanical Engineering Department Solid Mechanics Lab (SML) provided all test equipment necessary for this thesis study. The primary test equipment utilized was the Material Test System 810, which is used to test material specimens and components at loads up to 55 kips, tension or compression, with a 6 inch actuator stroke, static or dynamic. A pictorial drawing of the system is shown in Figure (1). The MTS system, which was acquired in 1985, operates on a closed loop principle. A command signal, an analog program voltage representing the desired load, stroke or strain to be applied to the specimen, is compared to a feedback signal that represents the actual load, stroke or strain measured by transducers. Any deviation between command and feedback causes a corrective control signal to be applied to a servovalve. The servovalve, in response to the control signal, causes the actuator to stroke in a direction required to reduce the deviation to zero. A diagram of this closed loop control along with other system components is shown in Figure (2).

Through manipulation of the system controls, various tests can be conducted, such as constant amplitude fatigue tests, crack initiation or crack growth tests, stress relaxation, creep, constant cycle fatigue and tensile tests.

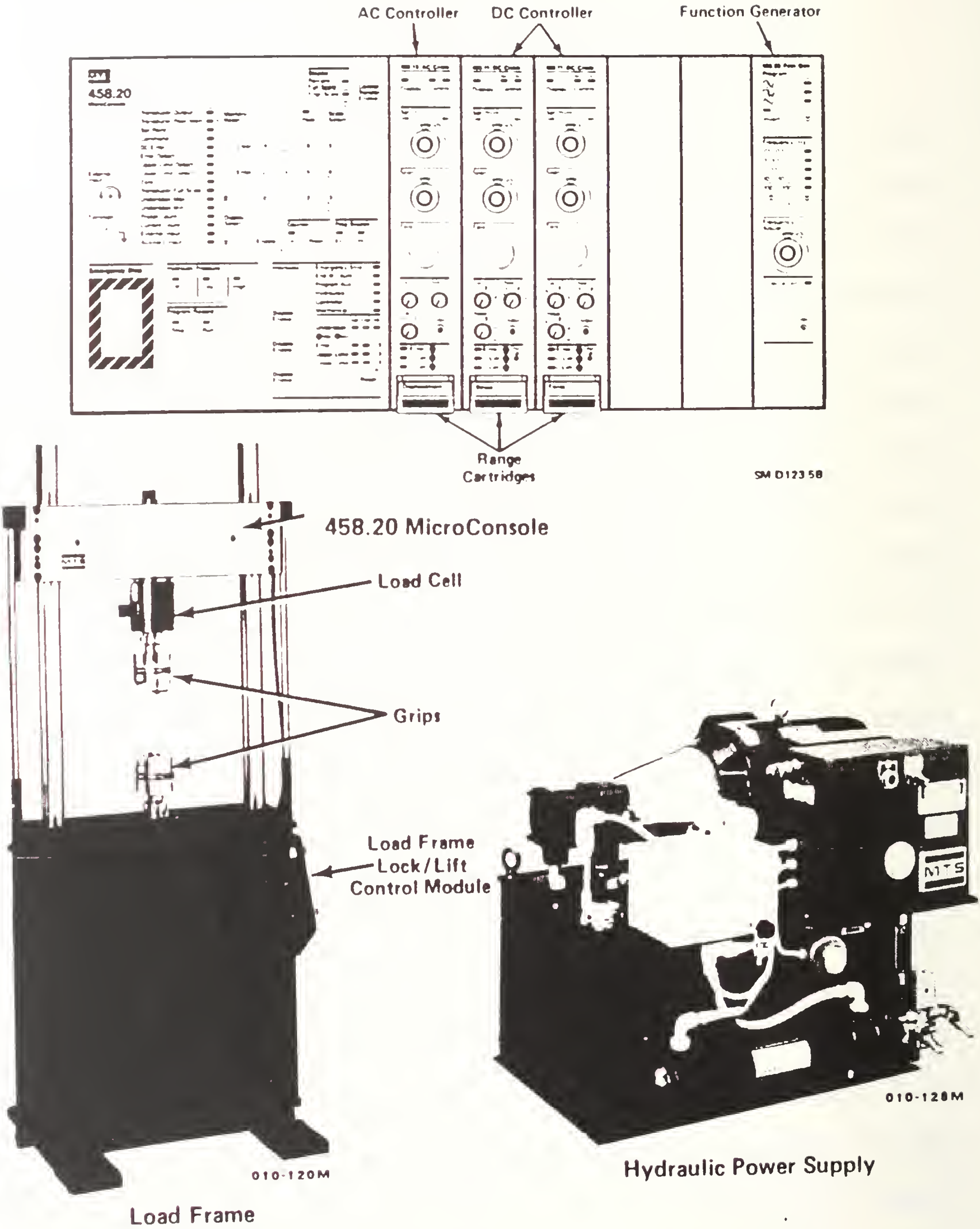


Figure 1: Material Test System

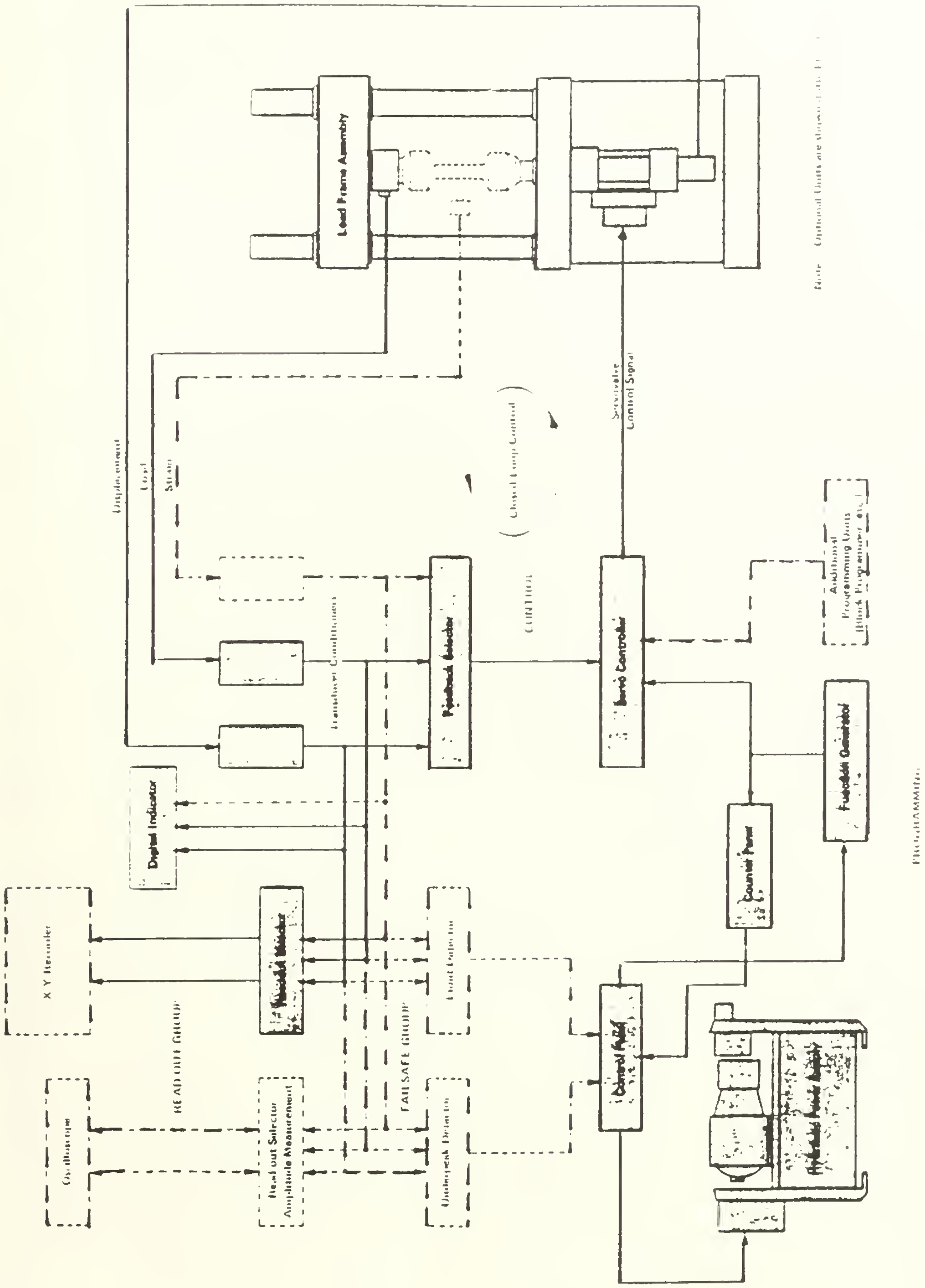


Figure 2: Closed Loop Control

A hydraulic power supply (model 506.01d) delivers 3.1 gallons per minute at 3000 psi to the load frame, which contains the Load Cell rated at 55 kips. Mechanical grips designed for tensile testing require the operator to impart a pre-load to initially hold the specimen. As the load increases on hard or tough materials this pre-load may be insufficient and allow slippage due to a load decline during the initial phase of the test or during load reversals, or it is possible to exert enough pre-load initially that a stress concentration at the end of the grip wedge may cause failure at that point, rendering the test invalid. Hydraulic grips on the other hand apply a constant force throughout the test eliminating load fall off, slippage or excessive gripping pressures. The MTS 810 utilizes 647 Hydraulic wedge grips as shown in Figure (3).

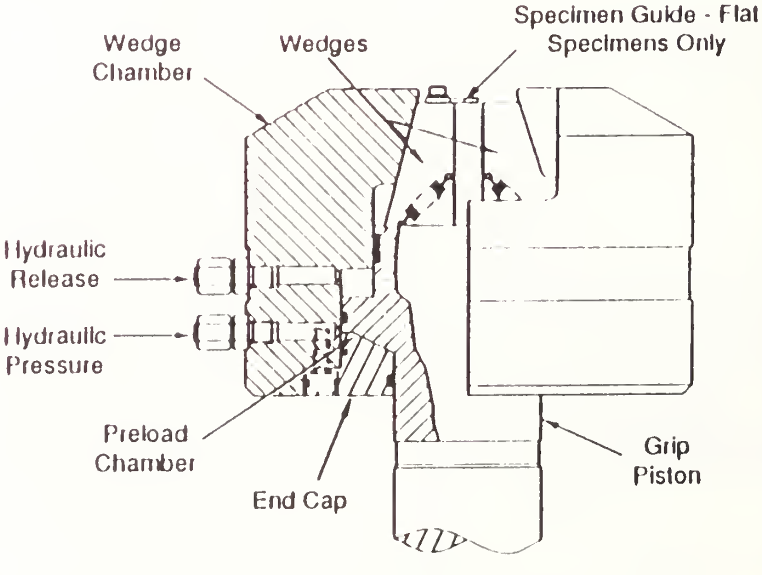


Figure 3: Hydraulic wedge grips

The machine 410.8 Function Generator is a versatile instrument capable of generating stable electrical functions (waveforms) for systems programming. The Function Generator can be set up to provide sine, haversine, and haversquare waveforms as well as ramp waveforms for test program command. Examples of each are shown in Figure (4).

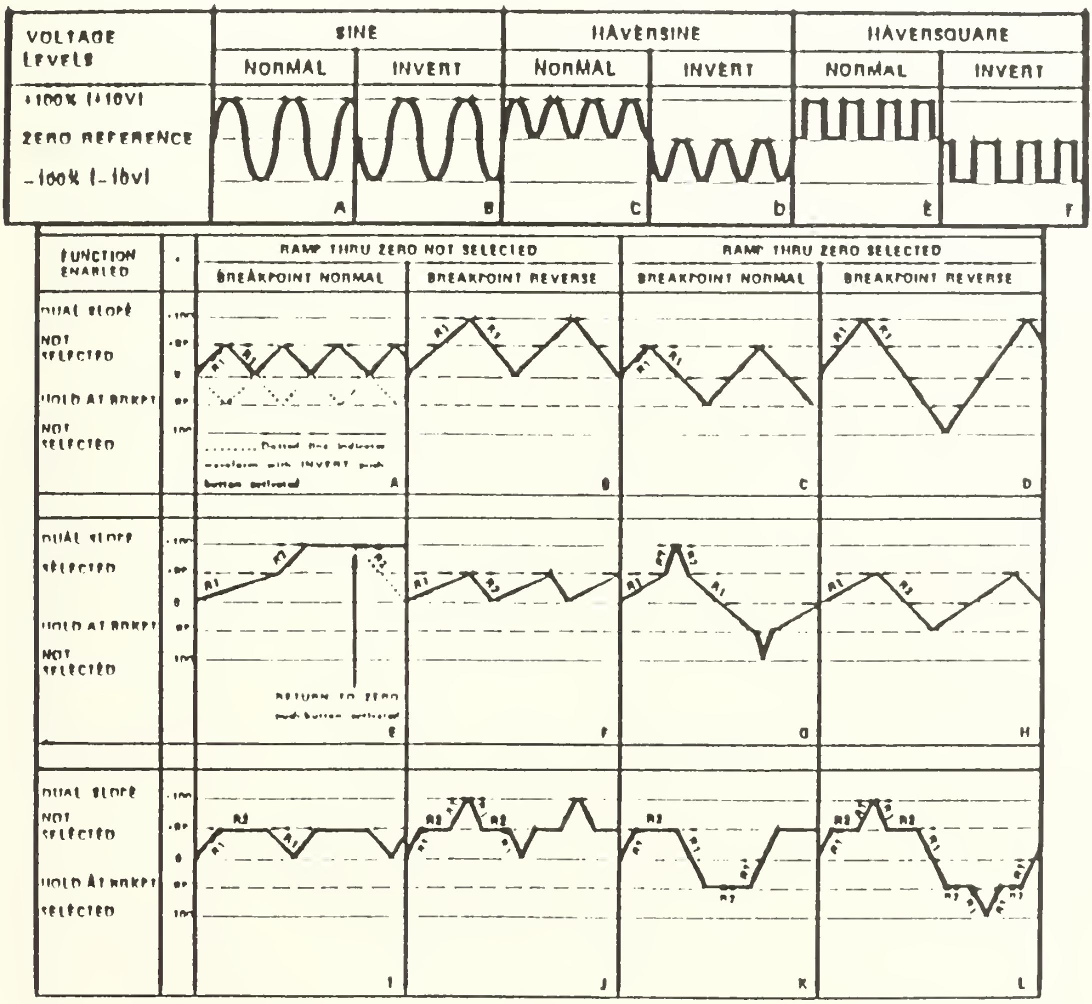


Figure 4: MTS waveforms

Most of the programming was done on the 458.20 Microconsole which is shown in Figure (5), along with the interchangeable range cartridges. For this thesis, range cartridges were chosen just larger than the maximum expected values. These were the 458.13 AC Displacement Controller (+/- 0.5 in.), the 458.11 DC Load Controller (+/- 5 kips) and the 458.11 DC Strain Controller. The extensometer used was the 632.13B20 model, which has a gage length of 0.5 inches and a range of +/- 0.075 inches. This corresponds to a +/- 0.150 in/in strain range. The strain gage extensometer used is shown in Figure (6).

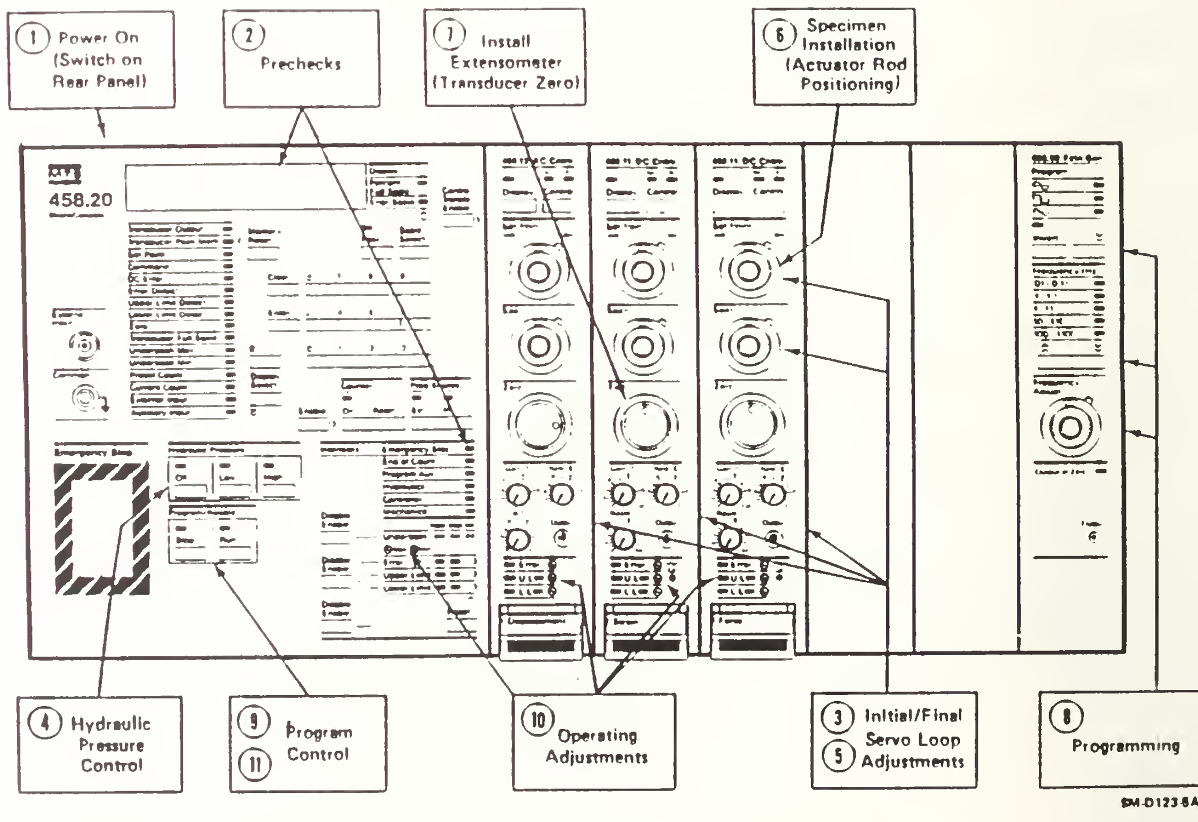
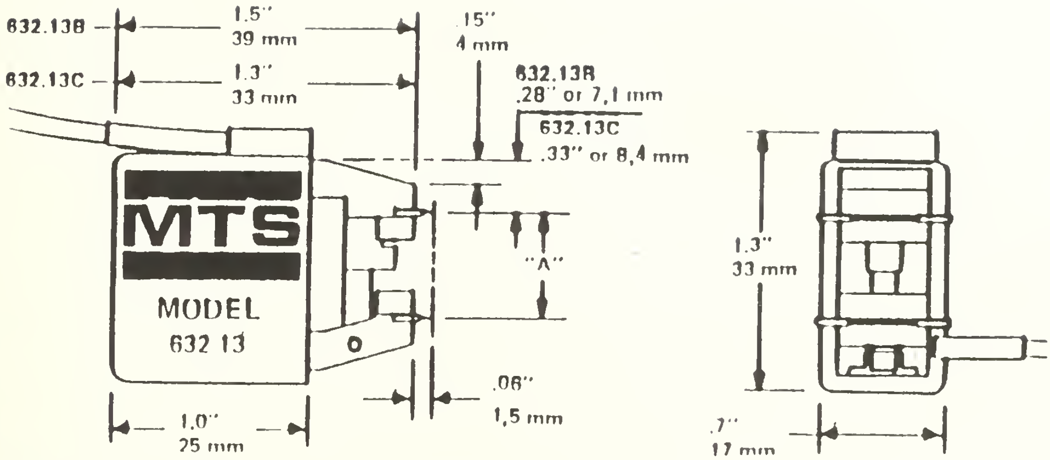


Figure 5: MTS Microconsole



MODEL English / Metric	632.13B 20 / 632.13C 20	632.13B 21 / 632.13C 21	632.13B 23 / 632.13C 23
Gage Length (Dimension A)	.500" ± .002 10mm	.500" ± .002 10mm	.500" ± .002 10mm
Max. Range of Travel (Strain)**	± 150 strain	± 150 strain	± 150 strain
Linearity***	0.25% of range	0.25% of range	0.25% of range
Ranges where extensometer may be calibrated to ASTM Class B1 Class C	 0 to .04 0 to .15	 0 to .04 0 to .15	 0 to .04 0 to .15
Max. Hysteresis	0.1% of range	0.1% of range	0.1% of range
Temperature Range	-115° to 250°F	-450° to 150°F	-450° to 350°F
Immersibility	Yes*	Yes*	Yes*
Max. operating frequency with negligible distortion	100 Hz	100 Hz	100 Hz
Weight (less cable and connector)	22 gm	22 gm	31 gm
Operating force full scale English / Metric	35 gm 45 gm	35 gm 45 gm	40 gm 50 gm
Recommended calibrated ranges for 10v full scale output from MTS transducer conditioner****	± .20 ± .10 strain ± .04 ± .02	± .20 ± .10 strain ± .04 ± .02	± .20 ± .10 strain ± .04 ± .02

Figure 6: Extensometer

III. EXPERIMENTAL PROCEDURES

A. SPECIMEN DESCRIPTION

Over 400 test specimens were prepared in accordance with the dimensions and specifications indicated in Figure (7) and set forth by ASTM Standards. Aluminum 7075-T6 sheets (4'x 8') were sheared in the short direction into 0.75 inch by 4 foot pieces. These were sheared into 6 inch long bars. They were then machined to meet ASTM standards, which call for the test section width to be between 2 and 6 times the thickness, the test section length to be greater than 3 times the test section width, and the radius of curvature to be at least 8 times the thickness. Furthermore, no milling cuts were greater than 0.1 inch, and the last 3 cuts were less than 0.01 inch in order to eliminate residual stresses caused by machining.

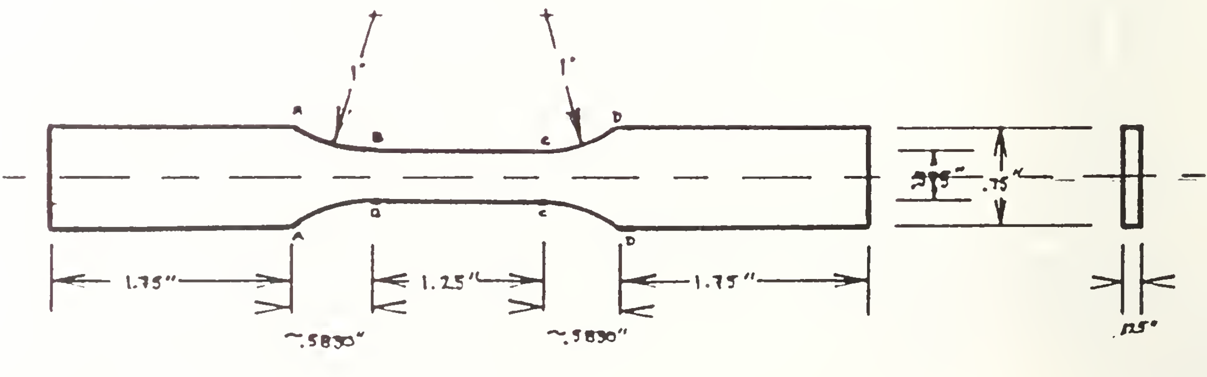


Figure 7: Test Specimen

B. TENSILE TESTS

Prior to mounting the specimens in the grips, the load was zeroed to null out the grip weight. The grips were then closed to securely hold the specimen. Load was adjusted to zero force, and the displacement and strain cartridge transducers were calibrated to their proper zero reading. Once this was completed, the machine could be switched to the desired controller.

Initial tensile tests were conducted to create stress-strain plots. The machine was driven via displacement, with a ramp signal. Load was recorded along the y-axis and later converted to stress, and displacement from the extensometer output was plotted along the x-axis and converted to strain. These tests also served to verify that the machine, controller, grips, extensometer, etc. were operating correctly and providing accurate data. The plots provided values which correlated with the parameters listed in Appendix (A). A summary of the above mentioned properties is shown in Table 1 of the Material Properties section.

C. CYCLIC TESTS

The MTS machine was then used to subject the specimens to sinusoidally alternating compressive and tensile loads. An attempt was made to create a representative strain life curve at zero mean strain. Twenty tests were conducted each for lives of approximately 1E3, 1E4, 1E5, and 1E6 cycles at their respective theoretical values of strain amplitude (0.007, 0.005, 0.003, and 0.0025 in/in) determined by the strain life equation ($\Delta\epsilon/2 = (\sigma f'/E)(2Nf)^b + \Delta\epsilon f'(2Nf)^c$). All tests were started at zero load and were run in strain control at 10 Hz. The set point was adjusted to obtain zero mean strain, and the span was utilized to produce the specified amplitude. A counter measured the reversals in transducer voltage feedback, and both displacement and strain limit detectors were adjusted to terminate the test upon specimen failure. The limit detectors were set on each range cartridge to 10% greater than the expected maximum and minimum values. This caused the test to be terminated upon specimen failure or if the controller outputs exceeded the desired response.

Probability plots were constructed for each strain amplitude and will be discussed further in the later sections. The 50% mean was used to produce a strain life curve representative of typical ϵ-N curves found in the literature. The mean strain was then increased to 0.030 in/in and tests were conducted at the same four values of strain amplitude. This procedure was repeated again at 0.063 and 0.100 in/in mean strain.

IV. MATERIAL PROPERTIES

As mentioned earlier, Aluminum 7075-T6 was chosen for testing. This choice was made due to its availability, the abundance of corresponding data, and its widespread use in Naval aircraft and in the aircraft industry today. Its material properties are listed in Appendix (A). Uniaxial stress-strain curves were generated to verify experimental procedures and test data. The material was then fatigued cyclically to 50% of its life and cyclic stress-strain curves were created. The cyclic stress-strain curve is shown, along with the monotonic stress-strain curve, in Figure (8). From these plots, several material properties were determined and compared to published data. Young's modulus was determined by the slope of the initial portion of the curve. The ultimate stress came from the peak in the curve, while fracture stress and strain came from the breaking point. Then the strain hardening exponent was determined and the strength coefficient was calculated. The properties were determined for five different graphs and then averaged. This comparison is shown in Table (1). The stress-strain curves along with the experimental material properties are similar to published curves and data. This similarity provided confidence in the test equipment and procedures.

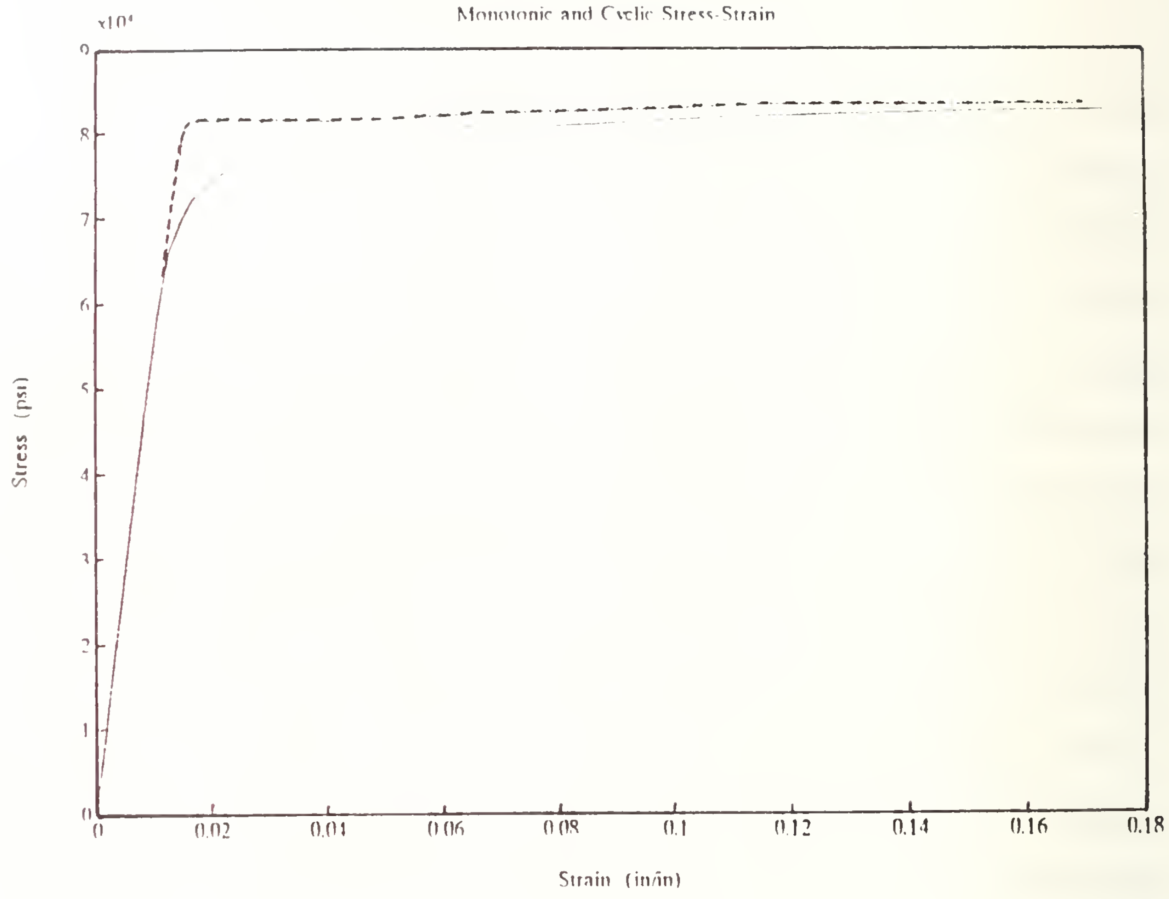


Figure 8: Stress-strain curve

Some consideration was given to dividing the strain data into its plastic and elastic portions; however, for the strain ranges used in these tests, the plastic portion was negligible when compared to its elastic counterpart. This is due to the lower level strain amplitudes necessary to obtain 1E3 cycles or more before failure.

TABLE 1: COMPARISON OF MATERIAL PROPERTIES

ALUMINUM 7075-T6

PARAMETER	PUBLISHED DATA	EXPERIMENTAL DATA
Ultimate stress Su	84 ksi	84 ksi
Yield stress Sy	68 ksi	66 ksi
Cyclic yld. stress Sy'	76 ksi	70 ksi
Strenth coeff. K	120 ksi	116 ksi
True frac strength σf	108 ksi	108 ksi
Fatigue str. coef. $\sigma f'$	191 ksi	151 ksi
Youngs modulus E	1.03E7 psi	1.10E7 psi
Strain hardening exponent n	0.110	0.093
Cyclic strain hardening exp. n'	0.146	0.132
True fracture ductility ϵf	0.41	0.46
Fatigue Ductility coefficient $\epsilon f'$	0.19	0.22

V. PROBABILITY DISTRIBUTION

> With the continued growth of the stock pile of experimental evidence gathered by fatigue investigators, it has become increasingly apparent that the basic problems of failure by fatigue are inherently statistical in nature. Fatigue data appear to exhibit more scatter than any other type of mechanical test data currently utilized by the design engineer. (Sinclair, 1990, p.867)

In order to obtain reliable estimates of means, standard deviations and percentiles of the data, 20 measurements were taken at each of four strain amplitudes, each of which were tested at four mean strain levels making a total of 16 different tests and 320 samples. Occasionally errors were made in using the test equipment, necessitating that the test results be thrown out and rerun. Results were only invalidated when it could be confirmed that the test was conducted improperly. Once all the data were compiled, the population mean and standard deviation were computed for normal, lognormal and Weibull distributions at each of the 16 levels of concern using AGSS, which is a comprehensive IBM software package resident on the Naval Postgraduate School main frame computer. AGSS is an interactive system for dimensional graphics, applied statistics and data analysis. The acquired data, along with the calculated population means and standard deviations, are shown in Appendix (B). The normal population standard deviation was then compared with the strain amplitude. According to Sinclair (3), fatigue data standard deviation will decrease at the higher strain ranges and shorter lives. Figure (9) plots the standard deviations versus strain amplitudes for four mean strain levels. These figures substantiate Sinclair's findings.

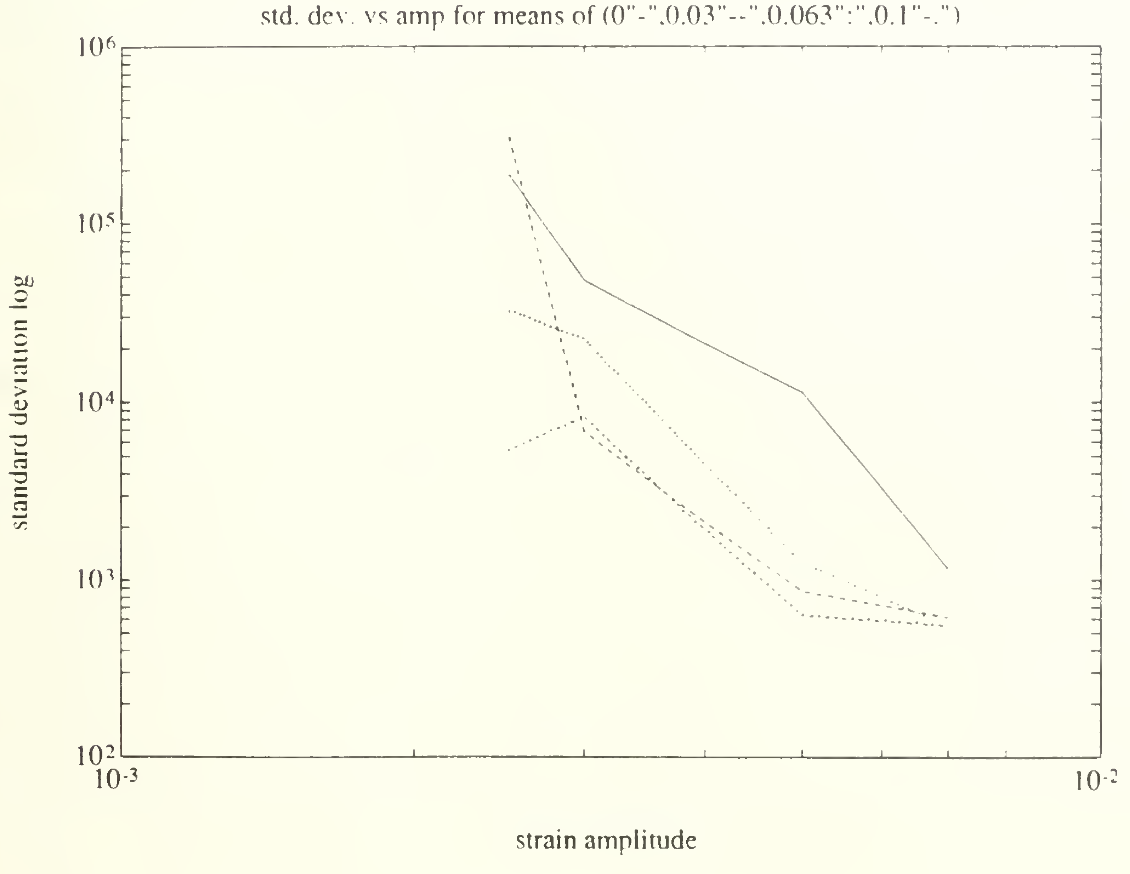


Figure (9): Standard deviation vs. strain amplitude

By means of probability plotting, a probability distribution function was selected to describe the data. Probability plotting is the plotting of data in specialized coordinates. The data (x) was plotted on the arithmetic or logarithmic horizontal axes, and the probability coordinates, or z, (where $z=\text{sign}(F(x) - 0.5)(1.238t(1 + .0262t)$ and $t=\{-\ln[4F(x)(1-F(x)]\}^{1/2}$) is plotted on the vertical axis. Weibull plots were also made of the data with ln(x) on the horizontal axis and z on the vertical axis where the value $z= \ln(-\ln(1-F(x)))$. F(x) is the cumulative distribution function of x, calculated by $F = (i - .5)/n$. After looking at the Kolmogorov-Smirnov and the Anderson-Darling statistics of the normal, Weibull and lognormal distribution functions, it became apparent that the normal distribution fit the data the best. A comparison of the normal, lognormal and Weibull fits is shown in Figure (10). Figure (11) through (13) show statistical numbers associated with the plots in Figure (10). On normal distribution plots, population means and standard deviations were estimated using the maximum likelihood estimator (MLE). Normal distribution plots are shown for the four mean strain levels in Figures (14) through (17).

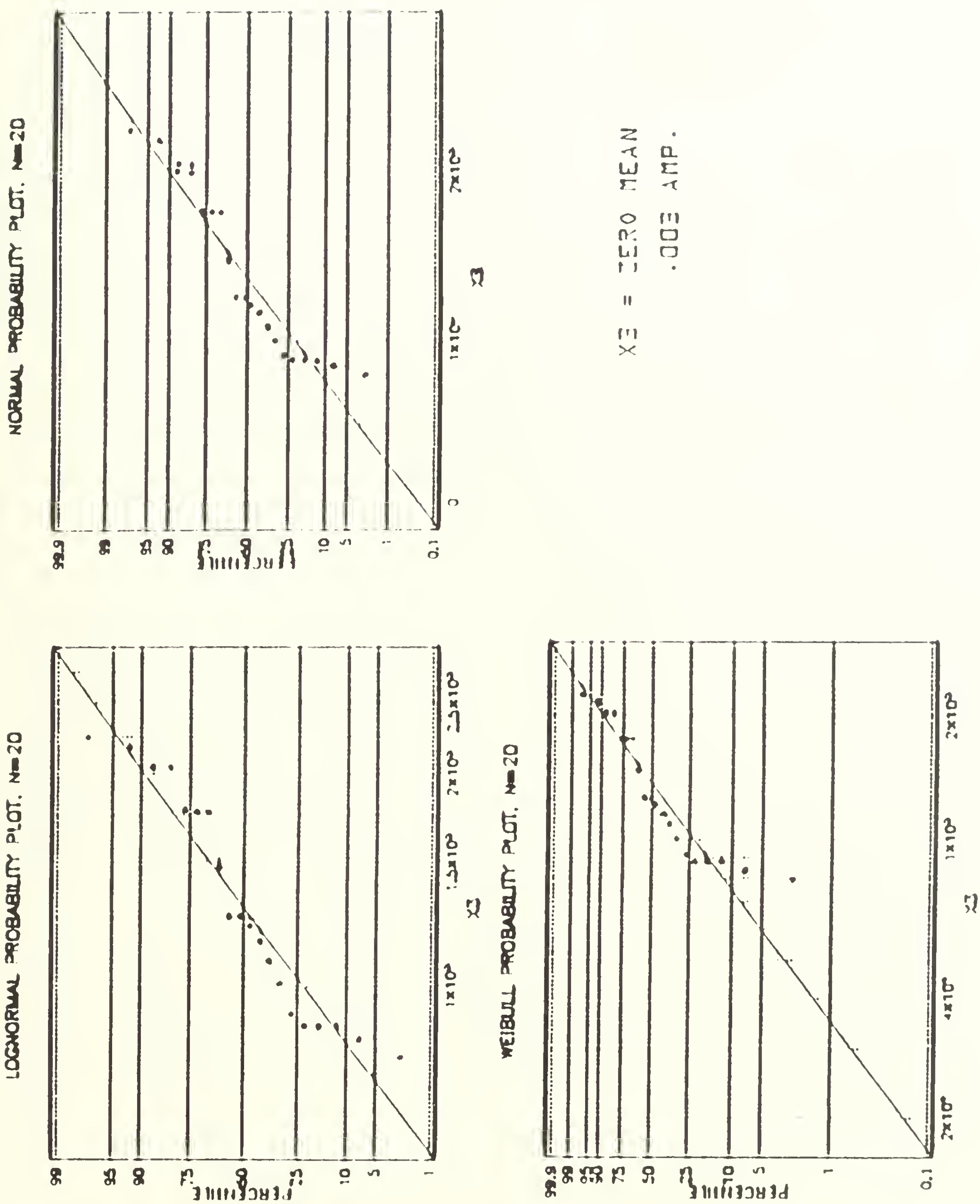


Figure (10): Normal / Lognormal / Weibull comparison

ANALYSIS OF NORMAL DISTRIBUTION FIT

DATA : X3
SELECTION : ALL
X AXIS LABEL : X3
SAMPLE SIZE : 20
CENSORING : NONE
FREQUENCIES : 1
EST METHOD : MAXIMUM LIKELIHOOD
CONF METHOD : EXACT

PARAMETER	ESTIMATE	CONF INTERVALS (95 PERCENT) LOWER	UPPER	COVARIANCE MATRIX OF PARAMETER ESTIMATES MU	SIGMA
MU	1.3739E5	1.1418E5	1.6060E5	1.1675E8	0.0000E0
SIGMA	4.8321E4	3.7702E4	7.2412E4	0.0000E0	5.8374E7

LOG LIKELIHOOD FUNCTION AT MLE = -244.09

	SAMPLE	FITTED
MEAN :	1.3739E5	1.3739E5
STD DEV :	4.9577E4	4.8321E4
SKEWNESS :	4.7201E1	0.0000E0
KURTOSIS :	1.7547E0	3.0000E0

* BASED ON MIDPOINTS OF FINITE INTERVALS

PERCENTILES	SAMPLE	FITTED
5 :	8.1733E4	5.7892E4
10 :	8.5893E4	7.5456E4
25 :	8.9665E4	1.0481E5
50 :	1.2378E5	1.3739E5
75 :	1.7759E5	1.6997E5
90 :	2.1124E5	1.9933E5
95 :	2.2087E5	2.1689E5

GOODNESS OF FIT TESTS

CHI-SQUARE : 3.8739
DEG FREED : 2
SIGNIF : 0.14414
KOLM-SMIRN : 0.19126
SIGNIF : 0.45727
CRAMER V M : 0.14625
SIGNIF : > .15
ANDER-DARL : 0.89393
SIGNIF : > .15

KS, AD AND CV SIGNIF LEVELS N…
EXACT WITH ESTIMATED PARAMETERS

NOTE: A SMALL SIGNIFICANCE LEV…
(E.G. P .01) INDICATES LACK OF FI…

CHI SQUARE GOODNESS OF FIT TABLE

LOWER	UPPER	OBS	EXP	O-E	((O-E)**2)/E
-INF	9.6625E4	6	3.9888	2.0112	1.0141
9.6625E4	1.2078E5	3	3.3218	-0.32182	0.031176
1.2078E5	1.4494E5	3	3.9306	-0.93061	0.22033
1.4494E5	1.6909E5	1	3.6412	-2.6412	1.9159
1.6909E5	+INF	7	5.1176	1.8824	0.69243
TOTAL		20	20		3.8739

Figure (11): Statistics for Fig. (10) normal distribution

ANALYSIS OF LOGNORMAL DISTRIBUTION FIT

DATA : X3
SELECTION : ALL
X AXIS LABEL: X3
SAMPLE SIZE : 20
CENSORING : NONE
FREQUENCIES : 1
EST. METHOD : MAXIMUM LIKELIHOOD
CONF METHOD : EXACT

		CONF INTERVALS (95 PERCENT)		COVARIANCE MATRIX OF PARAMETER ESTIMATES	
PARAMETER	ESTIMATE	LOWER	UPPER	MU	SIGMA
MU	11.77	11.603	11.937	0.006035	0
SIGMA	0.34742	0.27107	0.52062	0	0.0030175

LOG LIKELIHOOD FUNCTION AT MLE = -242.63

	SAMPLE	FITTED
MEAN :	1.3730E5	1.3733E5
STD DEV :	4.9577E4	4.9186E4
SKEWNESS:	4.7291E1	1.1205E0
KURTOSIS:	1.7547E0	5.3124E0

* BASED ON MIDPOINTS OF FINITE INTERVALS

PERCENTILES	SAMPLE	FITTED
5:	8.1733E4	7.2998E4
10:	8.5893E4	8.2823E4
25:	8.9665E4	1.0229E5
50:	1.2378E5	1.2928E5
75:	1.7759E5	1.6340E5
90:	2.1124E5	2.0180E5
95:	2.2087E5	2.2897E5

GOODNESS OF FIT TESTS
CHI-SQUARE : 4.6416
DEG FREED: 2
SIGNIF : 0.098203
KOLM-SMIRN : 0.16584
SIGNIF : 0.64729
CRAMER-V M : 0.10164
SIGNIF : > .15
ANDER-DARL : 0.68521
SIGNIF : > .15

KS, AD, AND CV SIGNIF. LEVELS NOT EXACT WITH ESTIMATED PARAMETERS

NOTE: A SMALL SIGNIFICANCE LEVEL (EG P .01) INDICATES LACK OF FIT

CHI-SQUARE GOODNESS OF FIT TABLE

LOWER	UPPER	OBS	EXP	O-E	((O-E)**2)/E
-INF	9.6625E4	6	4.0199	1.9801	0.9754
9.6625E4	1.2078E5	3	4.4279	1.4279	0.46047
1.2078E5	1.4494E5	3	4.1307	1.1307	0.30951
1.4494E5	1.6909E5	1	3.0246	2.0246	1.3552
1.6909E5	+INF	7	4.397	2.603	1.541
TOTAL		20	20		4.6416

Figure (12): Statistics for Fig. (10) lognormal

ANALYSIS OF WEIBULL DISTRIBUTION FIT

```
DATA           : X3
SELECTION      : ALL
X AXIS LABEL   : X3
SAMPLE SIZE    : 20
CENSORING      : NONE
FREQUENCIES    : 1
EST METHOD     : MAXIMUM LIKELIHOOD
CONF METHOD    : ASYMPTOTIC NORMAL APPROXIMATION
```

		CONF. INTERVALS (95 PERCENT)		COVARIANCE MATRIX OF PARAMETER ESTIMATES	
PARAMETER	ESTIMATE	LOWER	UPPER	C	
C (SHAPE)	3.1051E0	2.0488E0	4.1614E0	0.29033	2.1854E3
(SCALE)	1.5416E5	1.3109E5	1.7723E5	2105.4	1.3851E8

LOG LIKELIHOOD FUNCTION AT MLE = -243.66

	SAMPLE	FITTED
MEAN :	1.3739E5	1.3788E5
STD DEV :	4.9577E4	4.8587E4
SKEWNESS:	4.7291E-1	5.1277E-1
KURTOSIS:	1.7547E0	1.2842E0

* BASED ON MIDPOINTS OF FINITE INTERVALS

PERCENTILES	SAMPLE	FITTED
5:	8.1733E4	5.9231E4
10:	8.5893E4	7.4683E4
25:	8.9665E4	1.0321E5
50:	1.2378E5	1.3700E5
75:	1.7759E5	1.7126E5
90:	2.1124E5	2.0166E5
95:	2.2087E5	2.1950E5

GOODNESS OF FIT TESTS

```
CHI-SQUARE :   3.3067
  DEG FREED:   2
SIGNIF     :   0.19142
KOLM-SMIRN :   0.18408
  SIGNIF   :   0.50683
CRAMER-V M :   0.12839
  SIGNIF   :   > .15
ANDER-DARL :   0.78966
  SIGNIF   :   > .15
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EXACT WITH ESTIMATED PARAMETER

NOTE: A SMALL SIGNIFICANCE LE
(EG. P .01) INDICATES LACK OF F

CHI-SQUARE GOODNESS OF FIT TABLE

LOWER	UPPER	OBS	EXP	O-E	((O-E)**2)/E
-INF	9.6625E4	6	4.1798	1.8202	0.79267
9.6625E4	1.2078E5	3	3.3047	0.30473	0.028099
1.2078E5	1.4494E5	3	3.7569	0.75693	0.1525
1.4494E5	1.6909E5	1	3.4828	2.4828	1.7699
1.6909E5	+INF	7	5.2758	1.7242	0.5635
TOTAL		20	20		3.3067

Figure (13): Statistics for Fig (10) Weibull

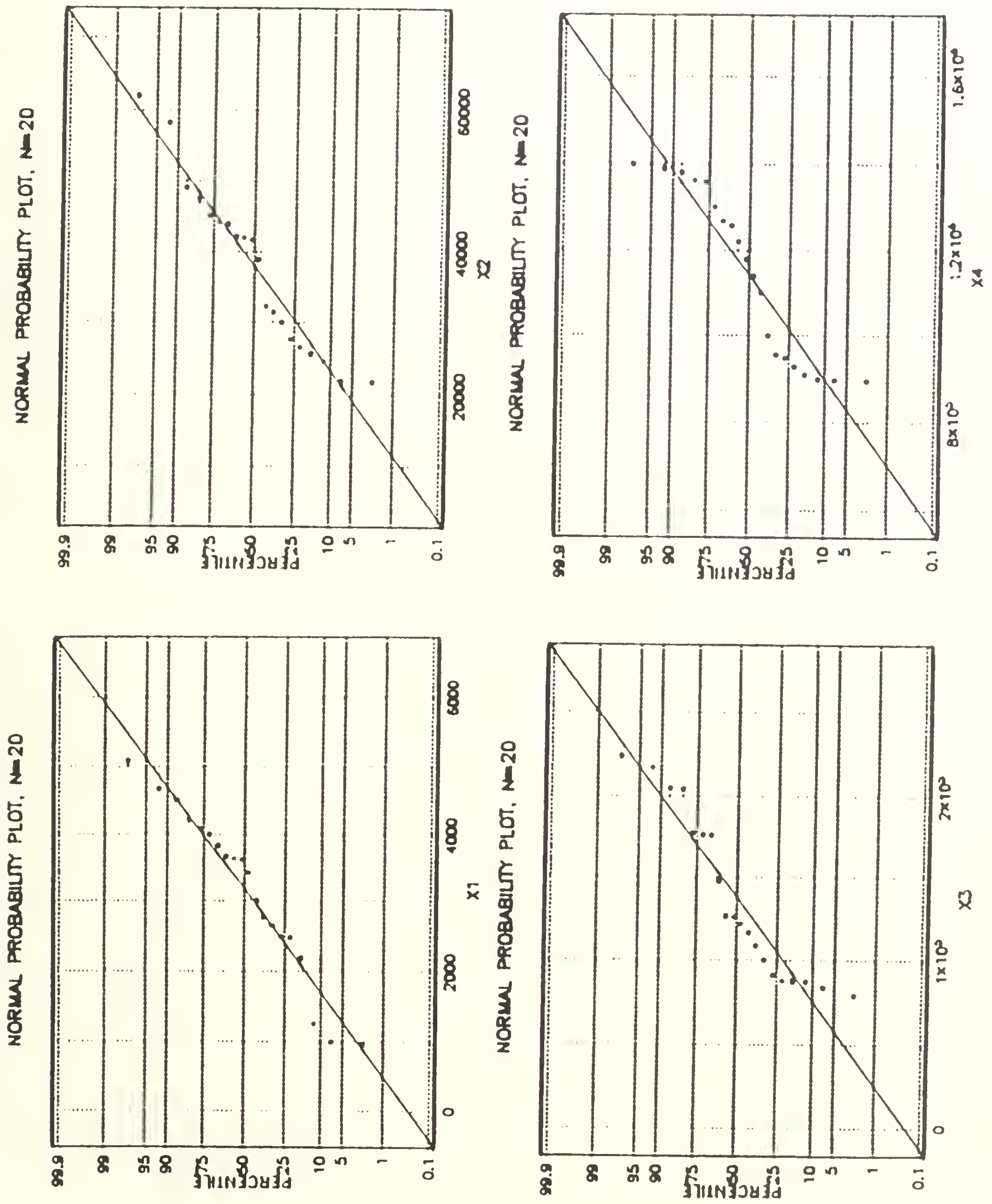

Figure (14): Probability distribution - 0 mean

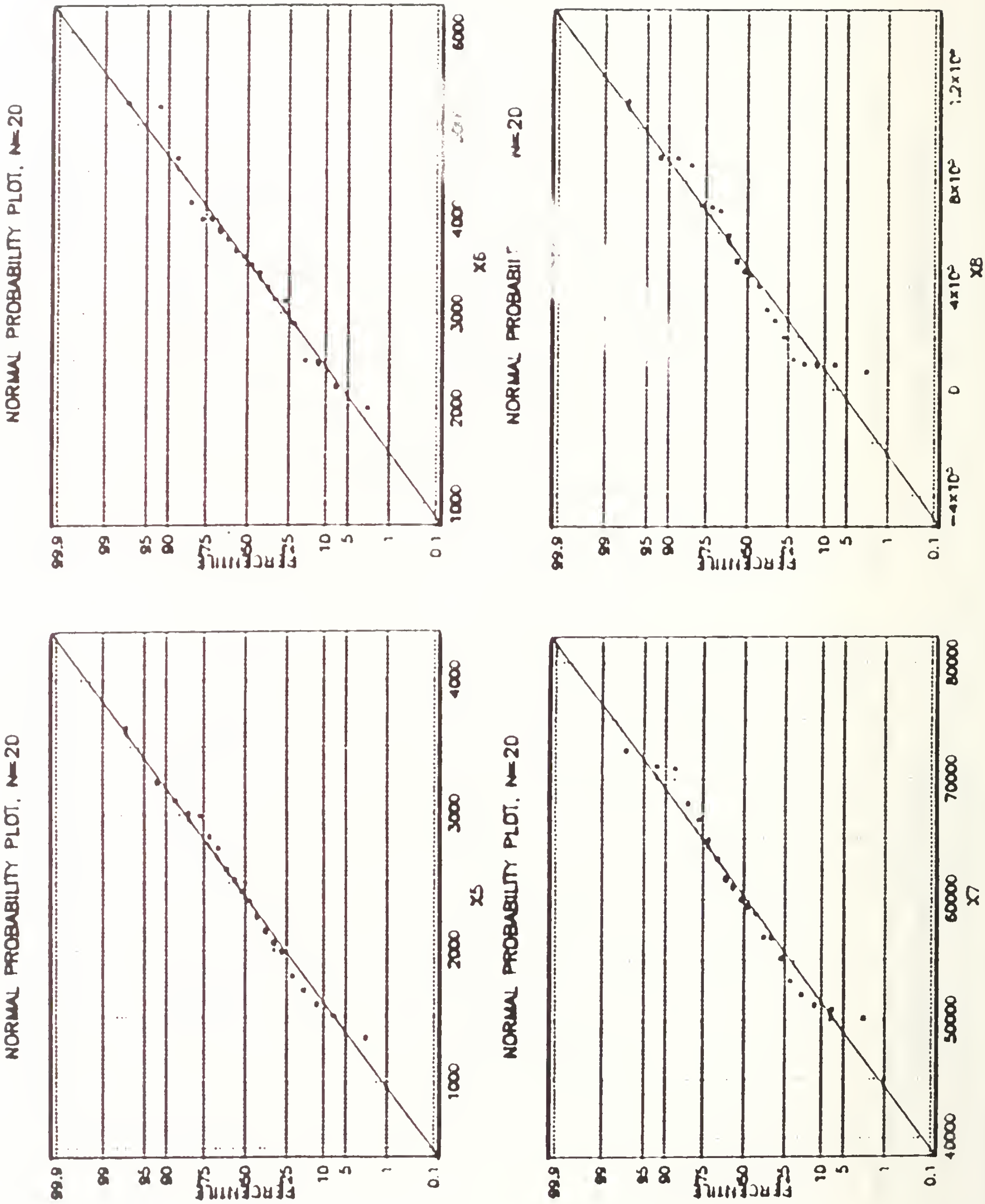

Figure (15): Probability distribution - 0.03 mean

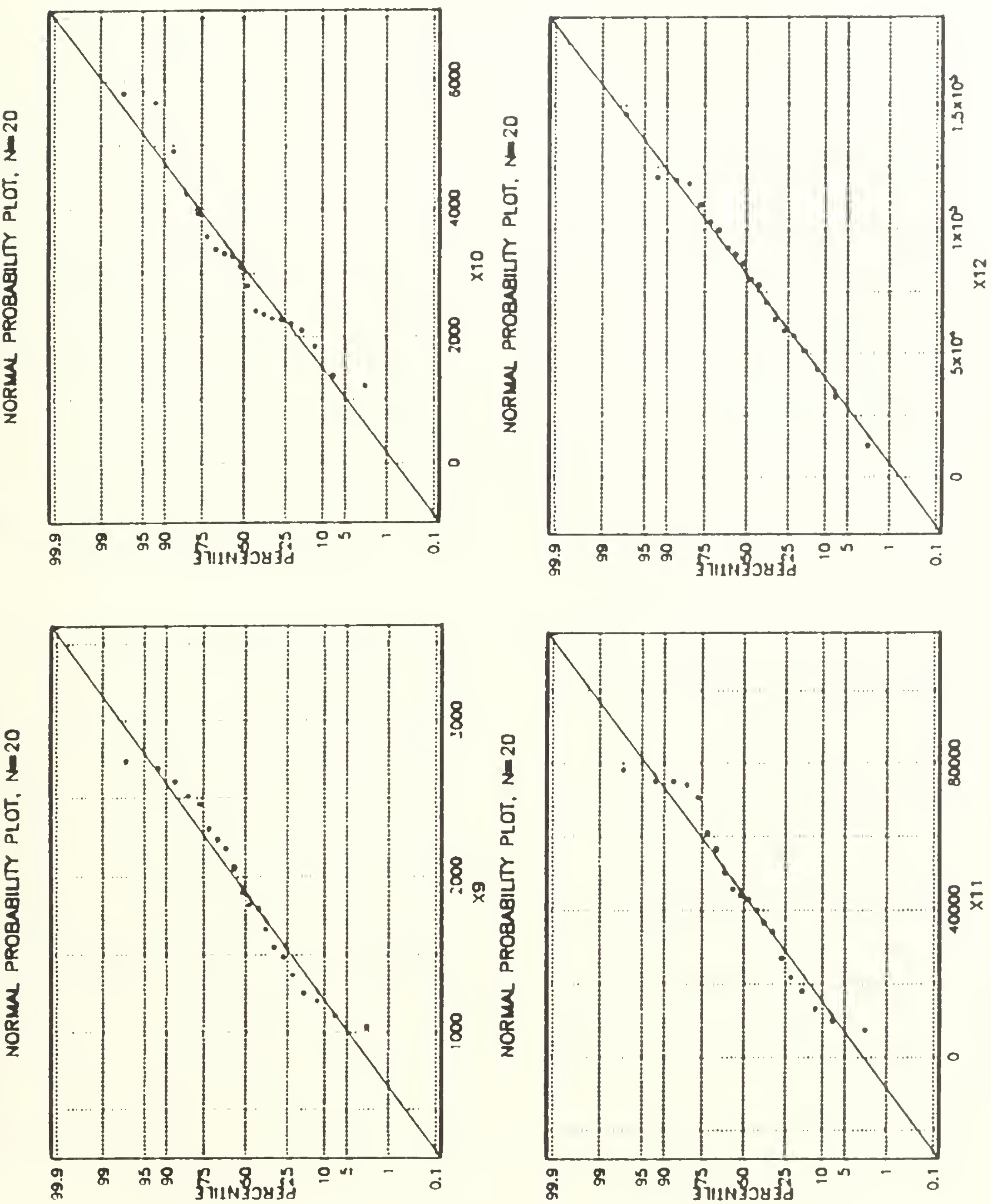

Figure (16): Probability distribution - 0.063 mean

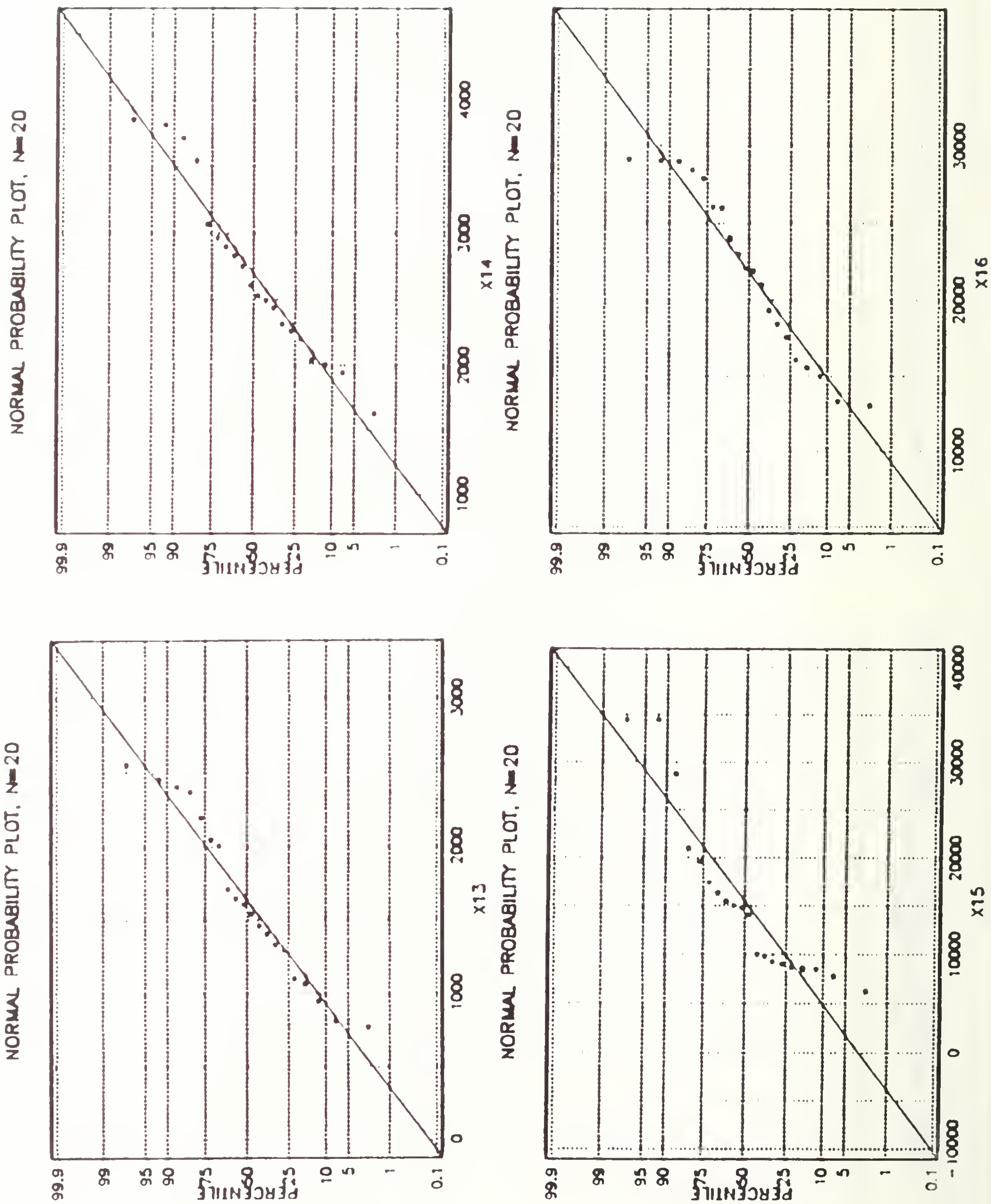

Figure (17): Probability distribution - 0.100 mean

VI. STRAIN-LIFE CURVES

After the data were compiled, the mean values were plotted on a log-log scale to obtain the standard strain-life curve as shown in Figure (18). Curves in the literature typically use an average of the data gathered, which would be a crude approximation to the 50% mean as a standard. However, due to the large spread in the data, curves were also created for 5%, 25%, 75% and 95% probability values. The curves are not affected significantly by using these values and actually show the scatter at various lives. Figure (19) demonstrates how the lives vary for certain probabilities and presents a Strain-life "band" between the 5% and 95% probability curves. When utilizing common strain life equations, the expected values tend to fall within this band. Material properties provided by Aerostructures predicts strain amplitudes of 0.0071, 0.0048, 0.0033 and 0.0023 for lives of 1E3, 1E4, 1E5 and 1E6 cycles respectively, while the classical strain life equation using parameters from the literature predicts 0.010, 0.0064, 0.0043 and 0.0031 respectively. These predictions have been added to Figure (19) and are annotated by the letter A for Aerostructures and S for strain life results.

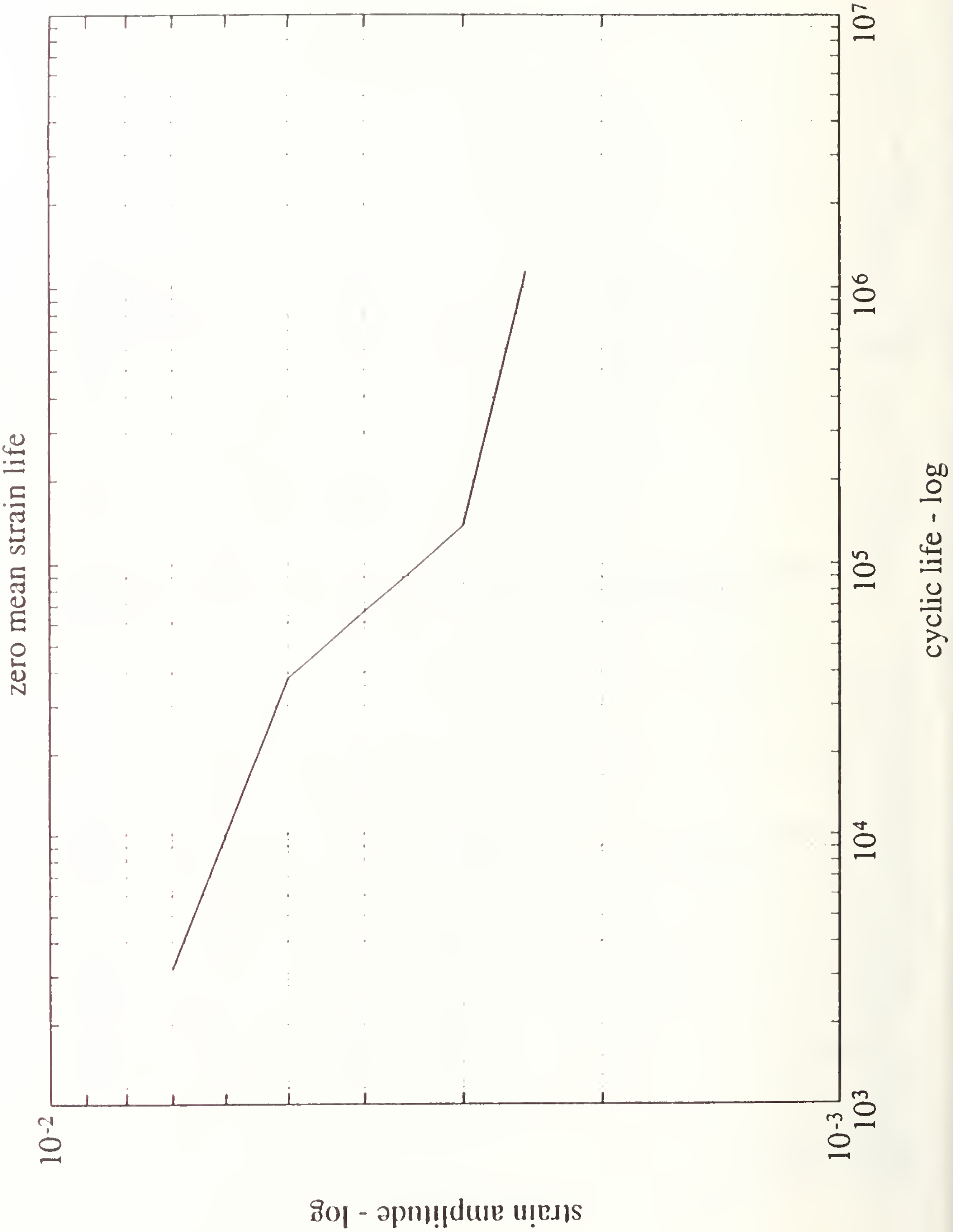

Figure (18): Strain life curve

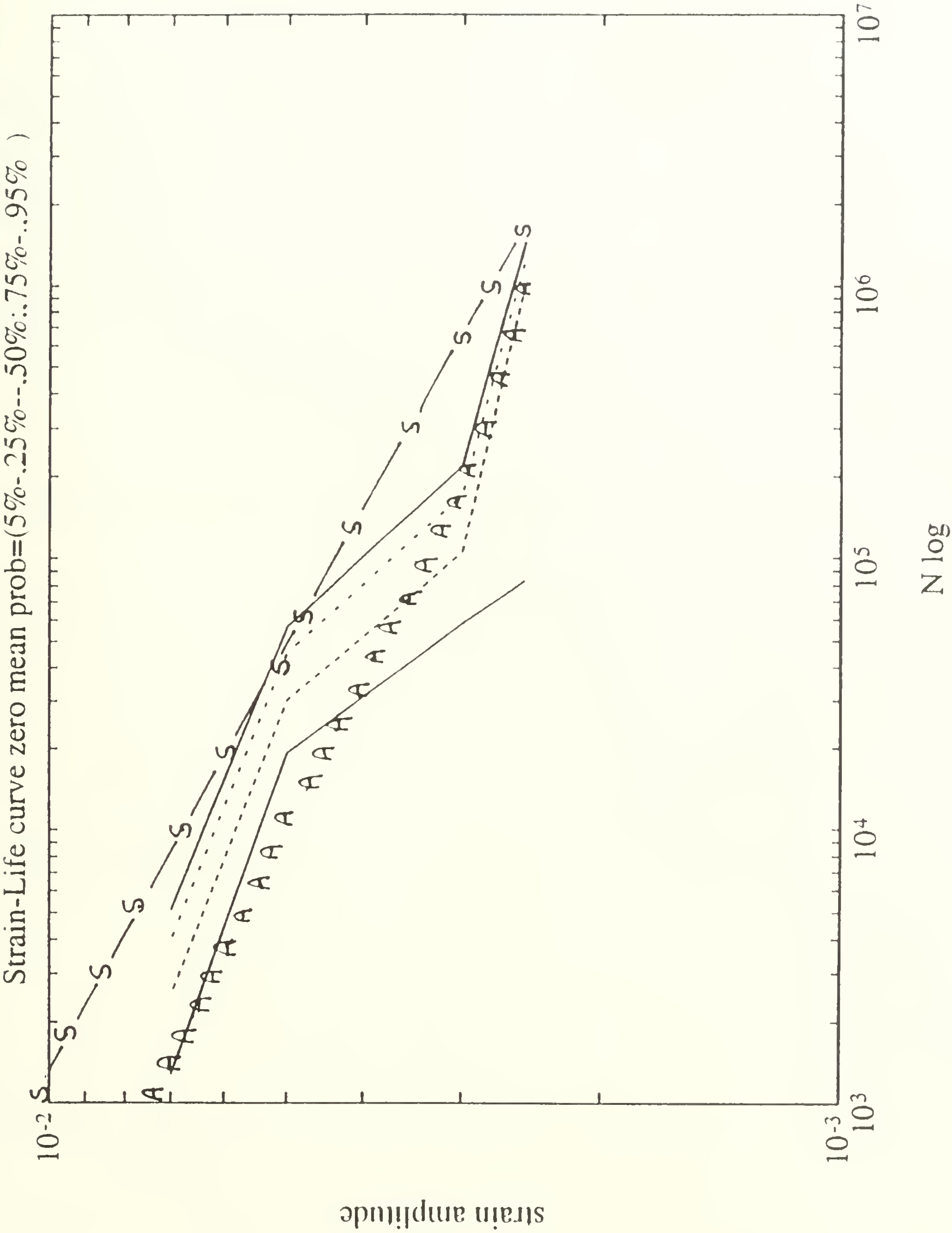

Figure (19): Strain life band

VII EFFECTS OF MEAN STRAIN

After establishing [illegible]ero mean, strain life curve, the mean strain was varied [illegible] 030, 0.063, and finally 0.100 in/in. Tests were run at e[illegible] evel, and distribution plots were created as mentioned before. From these plots, the means were determined and plotted to create the four strain life curves shown in Figure (20).

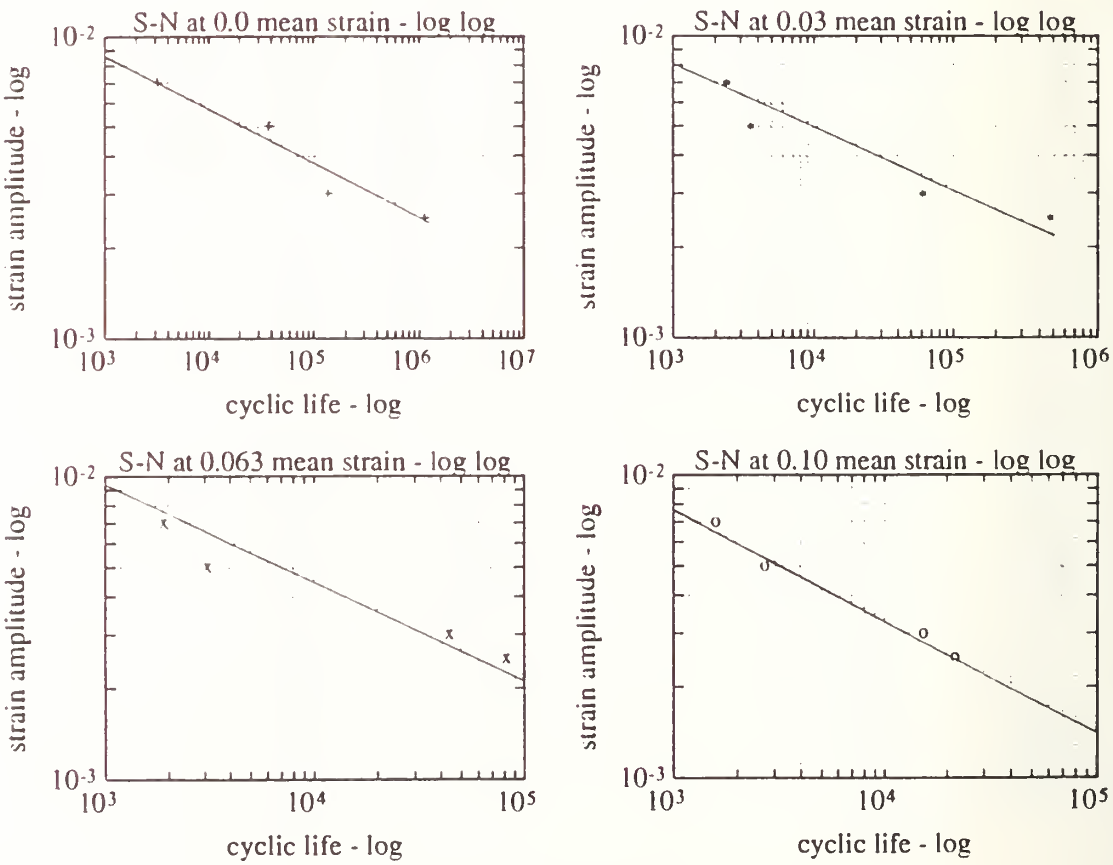

Figure (20): 4 mean strain life curves

These four curves were then combined to create the plot shown in Figure (21). This figure is quite similar to strain life curves in textbooks, which show the effect of mean stress. As with mean stress effects, it is evident that mean strain has very little effect on shorter lives, while its effect becomes more and more pronounced at longer lives. This is consistent with the observations that mean stress / mean strain effects are significant at low values of plastic strain, where the elastic strain dominates, but has little effect at shorter lives, where plastic strains are large.

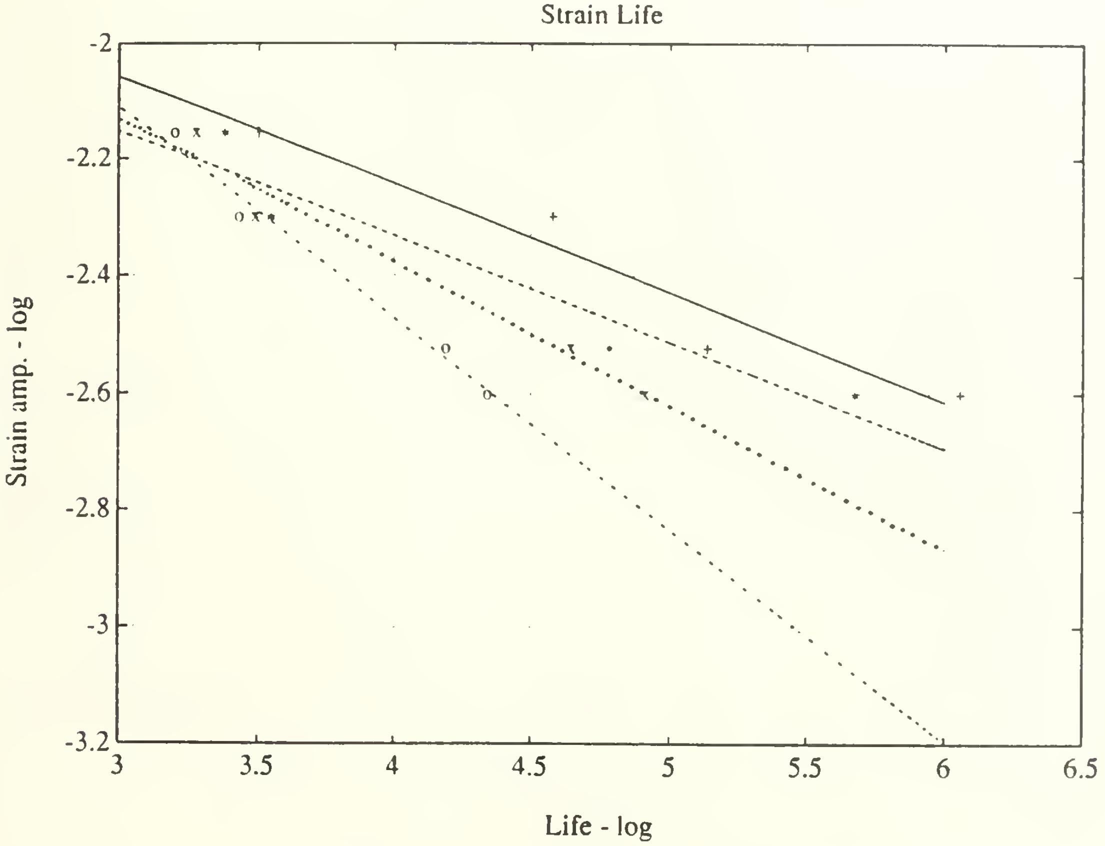

Figure (21): Strain life curves

Figure (22) shows plots of strain amplitude versus mean strain for four given lines of constant life. These four plots were then combined to create a graph very similar to what is known as a Haigh diagram. This "strain Haigh" diagram suggests that for a given life as the mean strain increases, the strain amplitude necessary to achieve this life decreases. With further testing this diagram could be refined and even expanded to create a master diagram which includes the effects of amplitude ratio and stress or strain ratio.

While using the Aluminum 7075-T6 parameters shown in Appendix (A) and the strain life equations provide adequate results, the information provided by Aerostructures, (Ref 4), suggests that Al 7075-T6 is better modeled by the equation $\epsilon a = .02035*(Nf)^{-.1573} + 565860*(Nf)^{-3.1484}$. Where the total strain amplitude is divided into its first term (elastic part) and its second term (the plastic part). This same information does not however suggest any relationship between mean strain and the fatigue life. The strain life curves for the four mean strains suggest a relationship that is dependent upon both mean strain and the cyclic life. The strain amplitude versus mean strain curves shown earlier suggest a linear relationship to mean strain. The Aerostructures equation would most likely be amended by subtracting a third term to account for mean strain in the form of $(-\epsilon m*Nf^x)$. However at this point it would be premature to formulate an equation that matches these lines.

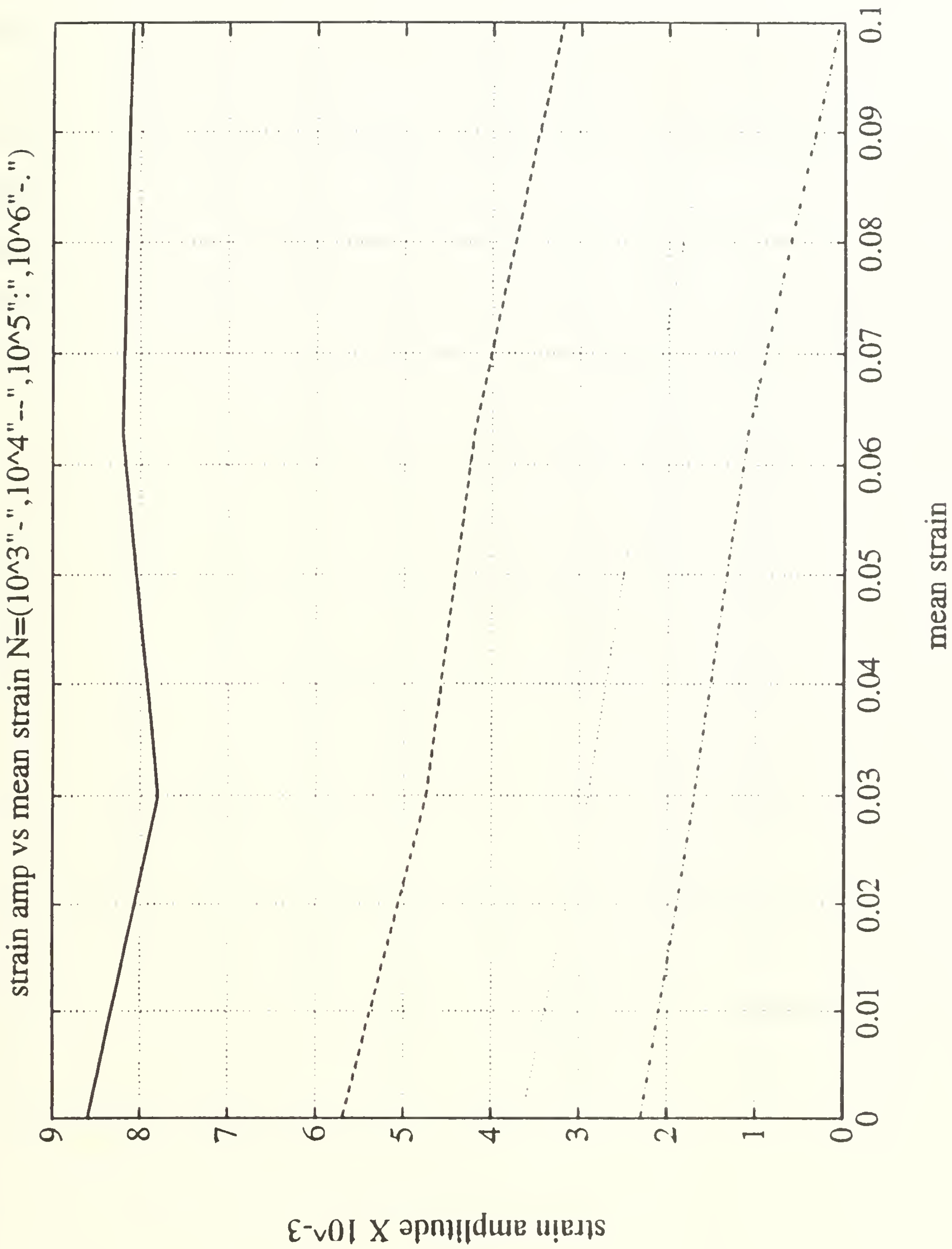

Figure (22): Strain amplitude vs mean strain

Further testing would be necessary to more precisely determine the strain life curves and add lines at additional mean strains. Several equations have been developed to account for mean stress effects on the strain life curve. Most notable are Morrow, and Manson and Halford. Figure (23) places Morrow's predictions on the previously mentioned Figure (22). It can be seen that Morrow equations consistently overpredict the fatigue life.

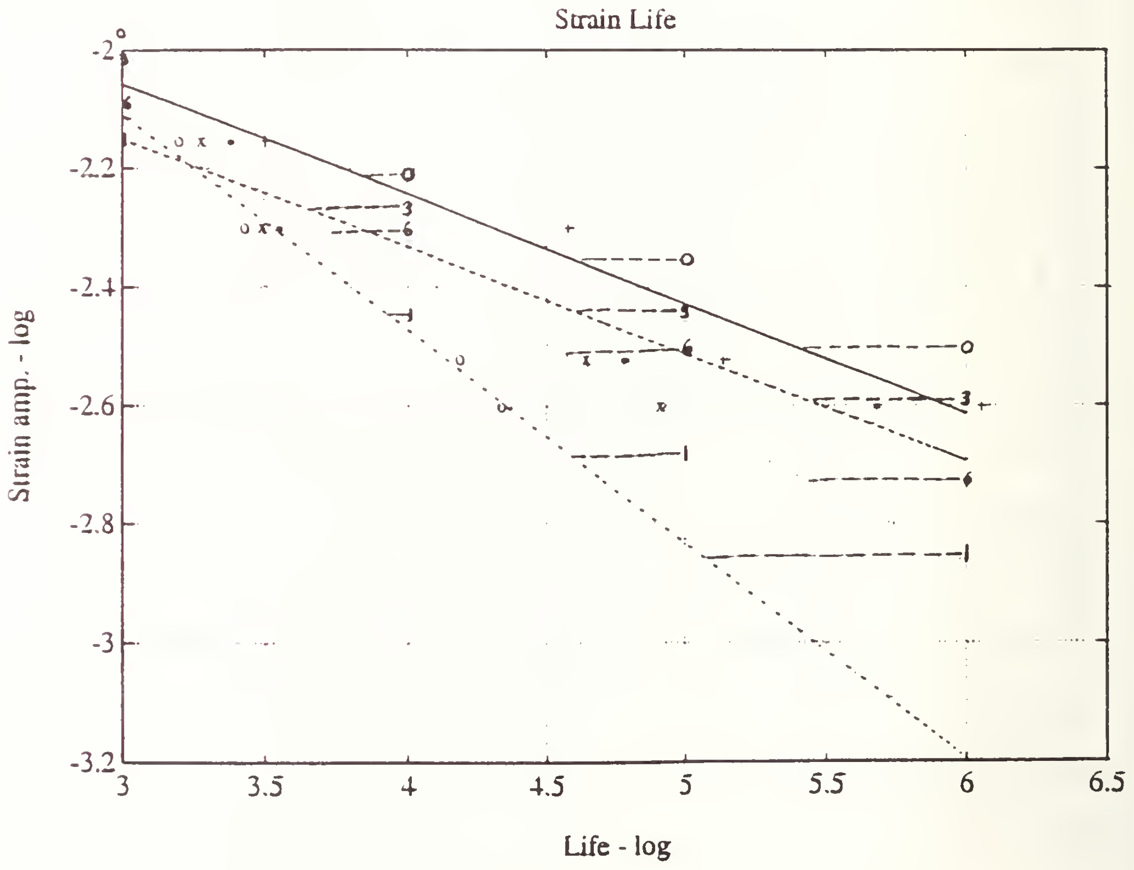

Figure (23): Morrow comparison

VIII. CONCLUSIONS AND RECOMMENDATIONS

Fatigue data has such a large amount of scatter associated with it, that a statistical treatment is required to express its values; however, much of the classical treatment of fatigue has not included statistical treatments. Researchers have utilized different parametric values to describe fatigue life and there are several different equations to account for mean stress effects, but most have not accounted for these effects statistically. It is because of this need to characterize large scatter and distribution of fatigue lives that a great deal of testing is required to obtain useful data.

This study has tested 320 samples and has shown the large scatter involved in fatigue testing and characterized it. Strain life curves for a range of percentiles, were created that are consistent with previously recorded results that provide some insight into mean strain effects. While this thesis has provided useful data on mean strain influences, more is required to reach any definitive relationships.

It is recommended that follow-on testing be conducted at intermediate lives, strain amplitudes and mean strains with special emphasis on mean strains between 0 and 0.03 in/in. In this way definite relationships may possibly be established with regards to mean strain effects. Eventually load histories from Navy aircraft can be analyzed using the results of this thesis and expected service lives predicted with specified statistical limits, which correctly incorporate the mean strain effect present in every load cycle.

The Navy is moving away from counting g's to determine aircraft life and toward strain monitoring, which requires mean strain influences to accurately predict fatigue life. It is because of this need that further testing should continue.

APPENDIX A. MATERIAL PROPERTIES

Material	Process Description	S_u (ksi)	S_y/S_y' (ksi/ksi)	K/K' (ksi/ksi)	n/n'	ϵ_f/ϵ_f'	σ_f/σ_f' (ksi/ksi)	b	c	S_f ($2N = 10^7$), (ksi)	S_f/S_u
Steel											
1005–1009	H.R. sheet	50	38/33	77/67	0.16/0.12	1.6/0.10	123/93	−0.109	−0.39	21	0.43
1005–1009	C.D. sheet	60	58/36	76/71	0.049/0.11	1.02/0.11	122/78	−0.073	−0.41	28	0.47
1020	H.R. sheet	64	38/35	107/112	0.19/0.18	0.96/0.41	103/130	−0.12	−0.51	22	0.34
0030	Cast steel	72	44/46		0.30/0.13	0.62/0.28	109/95	−0.082	−0.51	28	0.38
Man-Ten	H.R. sheet	74	57/54	—/114	0.20/0.11	1.02/0.86	118/117	−0.071	−0.65	38	0.51
1040	As forged	90	50/56	—	0.22/0.18	0.93/0.61	152/223	−0.14	−0.57	25	0.28
RQC-100	H.R. sheet	135	128/87	170/208	0.06/0.14	1.02/0.66	193/180	−0.07	−0.69	59	0.43
4142	Drawn at temp	154	152/108	—	—/0.18	0.35/0.22	162/210	−0.10	−0.51	44	0.28
4142	Q & T	205	200/120	—	0.051/0.17	0.66/0.45	265/265	−0.08	−0.75	73	0.36
4142	Q & T	280	250/195	—	0.048/0.13	0.43/0.09	315/315	−0.081	−0.61	85	0.31
4340	H.R. and annealed	120	92/66	—	—/0.18	0.57/0.45	158/174	−0.095	−0.54	40	0.33
4340	Q & T	180	170/110	299/—	0.066/0.14	0.84/0.73	240/240	−0.076	−0.62	71	0.40
4340	Q & T	213	199/120	—	—/0.15	0.48/0.48	226/290	−0.091	−0.60	68	0.32
9262	Annealed	134	66/76	253/200	0.22/0.15	0.16/0.16	151/151	−0.071	−0.47	50	0.38
9262	Q & T	145	114/94	—/197	0.14/0.12	0.41/0.41	177/177	−0.073	−0.60	55	0.38
Aluminum											
1100-0	As received	16	14/9	—	—/0.15	2.09/1.8	—/28	−0.106	−0.69	5	0.33
2024-T3	—	68	55/62	66/95	0.032/0.065	0.28/0.22	81/160	−0.124	−0.59	22	0.32
2024-T4	—	69	44/64	117/—	0.20/0.08	0.43/0.21	92/147	−0.11	−0.52	25	0.37
5456-H3	—	58	34/52	—	—/0.16	0.42/0.46	76/105	−0.11	−0.67	18	0.31
7075-T6	—	84	68/76	120/—	0.11/0.146	0.41/0.19	108/191	−0.126	−0.52	25	0.30

Material	Process Description	S_u (MPa)	S_y/S_y' (MPa/MPa)	K/K' (MPa/MPa)	n/n'	ϵ_f/ϵ_f'	σ_f/σ_f' (MPa/MPa)	b	c	S_f ($2N = 10^7$) (MPa)	S_f/S_u
Steel											
1005-1009	H.R. sheet	345	262/228	531/462	0.16/0.12	1.6/0.10	848/641	−0.109	−0.39	148	0.43
1005-1009	C.D. sheet	414	400/248	524/290	0.049/0.11	1.02/0.11	841/538	−0.073	−0.41	195	0.47
1020	H.R. sheet	441	262/241	738/772	0.19/0.18	0.96/0.41	710/898	−0.12	−0.51	152	0.34
0030	Cast steel	496	303/317	——	0.30/0.13	0.62/0.28	750/653	−0.082	−0.51	190	0.38
Man-Ten	H.R. sheet	510	393/372	—786	0.20/0.11	1.02/0.86	814/807	−0.071	−0.65	262	0.51
1040	As forged	621	345/386	——	0.22/0.18	0.93/0.61	1050/1540	−0.14	−0.57	173	0.28
RQC-100	H.R. sheet	931	883/600	1172/1434	0.06/0.14	1.02/0.66	1330/1240	−0.07	−0.69	403	0.43
4142	Drawn at temp	1062	1048/745	——	—0.18	0.35/0.22	1115/1450	−0.10	−0.51	310	0.28
4142	Q & T	1413	1379/827	——	0.051/0.17	0.66/0.45	1825/1825	−0.08	−0.75	503	0.36
4142	Q & T	1931	1724/1344	——	0.048/0.13	0.43/0.09	2170/2170	−0.081	−0.61	589	0.31
4340	H.R. and annealed	827	634/455	——	—0.18	0.57/0.45	1090/1200	−0.095	−0.54	274	0.33
4340	Q & T	1241	1172/758	1579/—	0.066/0.14	0.84/0.73	1655/1655	−0.076	−0.62	492	0.40
4340	Q & T	1469	1372/827	——	—0.15	0.48/0.48	1560/2000	−0.091	−0.60	467	0.32
9262	Annealed	924	455/524	1744/1379	0.22/0.15	0.16/0.16	1046/1046	−0.071	−0.47	348	0.38
9262	Q & T	1000	786/648	—1358	0.14/0.12	0.41/0.41	1220/1220	−0.073	−0.60	381	0.38
Aluminum											
1100-0	As received	110	97/62	——	—0.15	2.09/1.8	—193	−0.106	−0.69	37	0.33
2024-T3	—	469	379/427	455/655	0.032/0.065	0.28/0.22	558/1100	−0.124	−0.59	151	0.32
2024-T4	—	476	303/441	807/—	0.20/0.08	0.43/0.21	634/1015	−0.11	−0.52	175	0.37
5456-H3	—	400	234/359	——	—0.16	0.42/0.46	524/725	−0.11	−0.67	124	0.31
7075-T6	—	579	469/524	827/—	0.11/0.146	0.41/0.19	745/1315	−0.126	−0.52	176	0.30

APPENDIX B. EXPERIMENTAL DATA

MEAN STRAIN = 0.0 in/in

	X1 amp=.007	X2 amp=.005	X3 amp=.003	X4 amp=.0025
	971	21884	79316	897702
	1002	22046	84150	899463
	1261	24821	87636	900983
	2200	25783	87768	911760
	2489	26662	88058	929722
	2500	27663	91271	948989
	2660	30013	100540	956620
	2783	31468	108722	1000654
	3015	32266	116234	1100362
	3426	38904	121783	1140783
	3624	41768	125777	1180456
	3642	42036	126239	1221588
	3681	42255	147686	1259846
	3843	44016	176532	1270138
	4013	44322	177003	1302555
	4100	45167	178180	1359872
	4226	47562	204188	1364563
	4512	49127	204984	1381112
	4672	58236	217489	1390046
	5080	62000	224254	1400012
μ =	3185	37899	137391	1141411
σ =	1163	11378	48321	188965

31 hrs

MEAN STRAIN = 0.03 in/in

	X5 amp=.007	X6 amp=.005	X7 amp=.003	X8 amp=.0025
	1348	2014	50265	70015
	1512	2235	50987	96548
	1597	2477	51331	97036
	1704	2506	52242	101047
	1812	2896	53310	117108
	1987	3135	55204	202111
	2056	3152	56897	266504
	2144	3290	56943	307564
	2247	3438	58883	399176
	2369	3526	59468	445563
	2438	3603	60014	458118
	2527	3668	61156	497063
	2604	3789	61783	595181
	2756	3880	63464	686744
	2844	3997	64987	701168
	2997	4002	66663	707984
	3016	4176	68007	862564
	3111	4651	70977	887032
	3244	5200	71149	887564
	3650	5240	72465	1107363
μ =	2398	3544	60309	474672
σ =	616	864	6883	310335

59 m — 68 hr — 3.2 hr

11.9 hr — 43.5 hr — 273.7 hr

504.86

MEAN STRAIN = 0.063 in/in

	X9 amp=.007	X10 amp=.005	X11 amp=.003	X12 amp=.0025
	1030	1206	7500	12940
	1106	1370	10003	32431
	1202	1846	13250	43250
	1252	2099	18057	50893
	1369	2204	21989	57122
	1483	2256	27003	59257
	1546	2275	34256	63587
	1661	2350	36651	70633
	1794	2403	40077	77752
	1817	2800	43001	80008
	1892	3101	43987	86554
	2054	3267	45554	90119
	2176	3311	50117	92655
	2234	3380	56462	99875
	2304	3580	60987	103003
	2457	3929	70543	109968
	2512	4238	74054	118578
	2606	4900	74988	119972
	2690	5650	75051	120875
	2735	5801	78239	146113
μ =	1896	3098	44088	81779
σ =	540	1263	22620	33574

MEAN STRAIN = 0.100 in/in

	X13 amp=.007	X14 amp=.005	X15 amp=.003	X16 amp=.0025
	776	[illegible]	6246	13017
	812	[illegible]	7732	13298
	946	[illegible]	8501	14983
	1063	[illegible]	8545	15564
	1097	2197	8601	16088
	1288	2256	8988	17599
	1327	2311	[illegible]234	18424
	1402	2434	[illegible]6	19312
	1459	2486	[illegible]0008	20987
	1540	2528	14062	21897
	1605	2605	14783	22056
	1643	2747	15033	22987
	1706	2828	15507	24016
	2007	2897	16389	25987
	2046	2963	17422	26013
	2197	3069	19564	27883
	2373	[illegible]	21018	28413
	2404	[illegible]	[illegible]8762	28997
	2456	[illegible]	[illegible]113	29012
	2554	3850	[illegible]42	29135
μ =	1645	2692	15450	21783
σ =	552	630	8314	5401
	.045 hr/	.070 hr/	.43 hr/	.61 hr/
	10.9 hr	[illegible] hr	8.6 hr	22.1 hr

[illegible].1 hr

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